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MECHANICAL AND ELECTRONIC SYSTEMS
OF A GRAVIMETER

G. P. Arnautov, et al

Foreign Technology Division
Wright-Patterson Air Force Base, Ohio

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Block	Italic	Transliteration	Block	Italic	Transliteration
А а	<i>А а</i>	A, a	Р р	<i>Р р</i>	R, r
Б б	<i>Б б</i>	B, b	С с	<i>С с</i>	S, s
В в	<i>В в</i>	V, v	Т т	<i>Т т</i>	T, t
Г г	<i>Г г</i>	G, g	У у	<i>У у</i>	U, u
Д д	<i>Д д</i>	D, d	Ф ф	<i>Ф ф</i>	F, f
Е е	<i>Е е</i>	Ye, ye; E, e*	Х х	<i>Х х</i>	Kh, kh
Ж ж	<i>Ж ж</i>	Zh, zh	Ц ц	<i>Ц ц</i>	Ts, ts
З з	<i>З з</i>	Z, z	Ч ч	<i>Ч ч</i>	Ch, ch
И и	<i>И и</i>	I, i	Ш ш	<i>Ш ш</i>	Sh, sh
Й й	<i>Й й</i>	Y, y	Щ щ	<i>Щ щ</i>	Shch, shch
К к	<i>К к</i>	K, k	Ъ ъ	<i>Ъ ъ</i>	"
Л л	<i>Л л</i>	L, l	Ы ы	<i>Ы ы</i>	Y, y
М м	<i>М м</i>	M, m	Ь ь	<i>Ь ь</i>	'
Н н	<i>Н н</i>	N, n	Э э	<i>Э э</i>	E, e
О о	<i>О о</i>	O, o	Ю ю	<i>Ю ю</i>	Yu, yu
П п	<i>П п</i>	P, p	Я я	<i>Я я</i>	Ya, ya

* ye initially, after vowels, and after ъ, ь; e elsewhere.
 When written as ѐ in Russian, transliterate as yě or ě.
 The use of diacritical marks is preferred, but such marks may be omitted when expediency dictates.

FOLLOWING ARE THE CORRESPONDING RUSSIAN AND ENGLISH
DESIGNATIONS OF THE TRIGONOMETRIC FUNCTIONS

Russian	English
sin	sin
cos	cos
tg	tan
ctg	cot
sec	sec
cosec	csc
sh	sinh
ch	cosh
th	tanh
cth	coth
sch	sech
csch	csch
arc sin	\sin^{-1}
arc cos	\cos^{-1}
arc tg	\tan^{-1}
arc ctg	\cot^{-1}
arc sec	\sec^{-1}
arc cosec	\csc^{-1}
arc sh	\sinh^{-1}
arc ch	\cosh^{-1}
arc th	\tanh^{-1}
arc cth	\coth^{-1}
arc sch	sech^{-1}
arc csch	csch^{-1}
<hr/>	
rot	curl
lg	log

MECHANICAL AND ELECTRONIC SYSTEMS OF A GRAVIMETER

G. P. Arnautov, L. D. Gik, Ye. N. Kalish,
I. S. Malyshev, and Yu. F. Stus

In selecting a principle for constructing a basic mechanical instrument unit which would ensure free movement of a test mass, one fundamental problem arises - whether the initial velocity pulse should be transmitted to the mass in the direction opposite to acceleration (employ a symmetrical method of determination), or make the measurement with the initial velocity close to zero (asymmetrical method). Each of these methods has its own advantages and disadvantages.

The principal advantage of a symmetrical method of measurement is the fact that forces proportional to the velocity elicit considerably smaller measurement errors. This is explained by the fact that if the measurement is made in the same intervals of motion both in the same and opposite directions, then the direction of forces also varies, as a result of which, the average effect of their influence proves to be close to zero. As a result the effect of the deceleration forces can be disregarded. This quality is important but not decisive. Actually, the forces of superdynamic deceleration prove to be negligible small even under vacuum of the order of 10^{-6} torr, which is easily obtained by means of an oil-diffusion pump. In building portable instruments one can orientate oneself toward the use of the sealed off vacuum vessels.

The deceleration forces caused by the action of induction currents also prove to be negligibly small for a rational selection of the armature material and construction of an electromagnet of the holding system (we assume that the armature is part of the test mass).

The principal disadvantage of a symmetrical method is the fact that it is extremely difficult to transmit a substantial velocity pulse of translational motion to the test mass, having avoided the pulse of angular velocity. Actually, until free motion begins the test mass should be on a support rigidly connected to the base of the installation. Finite rigidity W is formed at the point of contact, which stores potential energy $\frac{F_0}{2W}$ under the effect of the holding force F_0 . Let r be the distance between the center of mass and the line of direction in which force F_0 acts. Then the angular velocity pulse

$$\frac{d\varphi}{dt} = \frac{1}{J_0} \int F(t) r dt. \quad (1)$$

Here J_0 - principal moment of inertia of a test mass. From the law of conservation of energy and law of conservation of pulse it follows that $\int F(t) dt = \frac{F_0}{\omega_0}$. Here ω_0 - natural frequency of a test mass-support system. Substituting this value of the force pulse into (1) we obtain:

$$\frac{d\varphi}{dt} = \frac{F_0 r}{\omega_0 J_0}.$$

In a system which employs a symmetric method it is difficult to achieve "acceleration" of a test mass such that when it is terminated, force F_0 evenly diminishes to zero. Furthermore, as shown by the experiment, it is very difficult to avoid lateral pulses of the accelerating system. It is these two factors that elicit pulses of angular velocity of a test mass, approximately one order higher than those when an asymmetrical method is used. This requires that the coincidence between the optical center of a reflector and the center

of mass be two orders more precise, which is difficult to realize technically.

The second disadvantage of a symmetrical method is the considerably greater seismic impact which is unavoidable during the acceleration of a test mass. This requires the use of various foundations for the unit which provides motion for a test mass and an interferometer unit which measures the movement.

After analyzing the advantages and disadvantages of both methods we decided in favor of an asymmetrical method of measurement and constructed two experimental versions of a gravimeter based on its principle. Figure 1 shows a mechanical illustration of the gravimeter. Angular reflector 2 which is in housing 3 falls in an evacuated tube 1 (Fig. 1). The prism at the top of the tube is held by electromagnet 4 whose magnetic circuit is made from ferrite. Flat ferrite plate 5 which is rigidly mounted on holder 3 closes the magnetic flow of electromagnet 4 and is held by it in the upper position until the circuit of the supply coil of electromagnet 4 opens.

The drop object which contains elements 2, 3 and 5 comes in contact in the extreme uppermost position with a fixed part of the gravimeter at three points. The three-point contact is accomplished by means of needles 6 which are rigidly connected to the upper flange 7 of tube 1. With their sharp ends these needles rest against "thrust bearings" 8 which are made from hard alloy T15K6T and mounted on the drop body. The raising of the drop body is accomplished by carriage 9 which, in its movement along the vertical, is held by electromagnet 10 which is actuated by electric motor 11. The movement of the carriage, switching in and off of the electromagnets is controlled by means of an electronic system which operates together with a position-sensitive switches. At the end of its free fall the drop body is caught by a spring-loaded wedge formed by three flat elastic guides 12.

The laser beams are let in and out through glass window 13 built into the lower flange 14. The evacuation of the tube is accomplished through connection 15 by means of a vacuum system (not shown in the figure) which consists of the backing pump VN-2M, fore tank, diffusion pump N5-S, nitrogen trap and system of vacuum locks. The pressure inside the tube is measured by the ionization-thermocouple vacuum gauge. In one mock-up the evacuated tube is made of glass in the other - stainless steel.

The selection of ferrite as the material for the magnetic circuit and the yoke holding the electromagnet is determined by the fact that, as shown by the experiments, such a holding system, as compared with magnets whose magnetic circuit is made from other materials (Armco, various magnetic steels), produces a lower pulse during the release, which causes twisting of the prism as it falls. Furthermore, the ferrite yoke made in the form of a thin ferrite plate has low residual magnetization which is essential for decreasing the effect of electromagnetic forces on the falling body.

The optical system of the gravimeter is described in [1]. The signal coming from a photomultiplier is amplified by a preamplifier and is fed to the input of the electronic calculation system. The function of this system is to determine the intervals of path and time during the motion of a test mass at least at two segments of its trajectory. Here it is possible both to fix the intervals of time and measure the intervals of path and, conversely, fix the intervals of path and measure the intervals of time. A more complex version is also possible as, for example, with the method of coincidences where the measured quantities are both path and time.

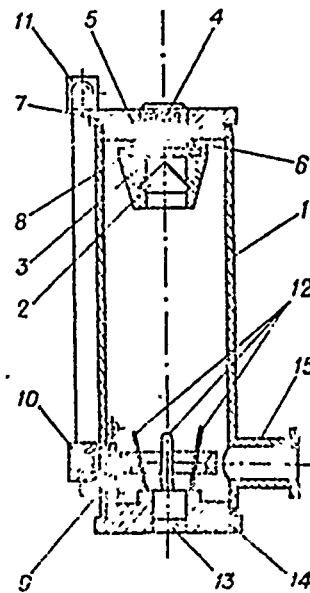


Fig. 1.

Calculational procedures in the second and third cases prove to be more cumbersome. To clarify this point we turn to the calculation formula which, in this case, can be conveniently written as

$$g = \left(\frac{N_2}{t_2} - \frac{N_1}{t_1} \right) \frac{\lambda}{t_2 + 2\Delta t - t_1}. \quad (2)$$

Here N_2 and N_1 - number of interference lines counted in the time intervals t_2 and t_1 , Δt - time shift between the calculation periods.

It is evident from (2) that calculations for the cases when t_1 and t_2 are the values being calculated require for each specific measurement result the determination of values which are reciprocal of t_1 , t_2 and $t_2 + 2\Delta t - t_1$, which is a cumbersome procedure, since due to the high accuracy of measurements we are forced to deal with cumbersome figures.

From the standpoint of processing of the results the first approach is simpler. Actually, in this case, the calculation is reduced to calculating relationship $K_1(N_2 - K_2 N_1)$. Here $K_1 = \frac{\lambda}{t_2(t_2 + 2\Delta t - t_1)}$ and $K_2 = t_2/t_1$ are constants for all measurements and can be predetermined. Thus, if the use of a computer is undesirable for any reason, the latter would be the method of choice.

Of considerable interest is the problem dealing with an optimum relationship between the time intervals t_1 , t_2 and Δt . It should be solved from the condition of minimization of the measurement errors. An analysis of [2] indicates that the case $t_1 = t_2 = \Delta t = 1/2 t_0$ corresponds to the optimum (here t_0 - maximally possible time period of measurement, determined by the dimensions of the installation); from this it is evident that the optimum is not the parallel version, as generally assumed, but a systematic version of selection of the measured intervals.

The principal advantage in constructing the electronic system with successive selection of measurement intervals consists of the fact that during the operational process of the installation it is possible to get by with one solitary counter. The idea here is not so much simplification as elimination of systematic errors associated with the delay in starting the calculation, which is unavoidable in every real system. The use of the same counter eliminates this error since the pulses of path and time pass through the same circuits.

The selection of successive intervals permits one to realize one more interesting possibility. The fact is that when $t_1 = t_2$, $k_2 = 1$. Thus, if during measurements, one uses a reversible counter with weight coefficient $1/K_1$, then the measurement result will yield directly the value of measurable value g in the corresponding system of units.

The main disadvantage of the measurement system with fixed time interval is insufficient resolution. Actually, based on the design concepts the attempt to have the path interval S_2 greater than the value on the order of 1 m is unsuccessful. This yields a resolution of $\frac{\lambda}{2S_2} = 3 \cdot 10^{-7}$. In actuality this number proves to be even larger.

Thus, in order to achieve high accuracy what is required is either the use of the time-amplitude device or an accumulation of measurement results for subsequent statistical processing. The fixing of the path intervals and the measurement of time enable one to obtain better resolution due to the fact that the signal frequency, which quantizes time intervals, can be increased to a value of the order of 100 MHz (the high-speed operation of the series-produced counters, for example Ch3-34, is considered). Thus, the measurement of time periods of the order of 0.2 s permits one to obtain a resolution of $5 \cdot 10^{-8}$, which requires considerably less data for statistical processing.

The calculation unit is a measurement system based on whose readings the gravity acceleration values are determined. This calculation unit was developed and tested in several types of modifications which permit one to realize measurement systems based both on the measurement of path intervals covered by a body in the given time intervals and the measurement of time periods in which a body covers certain distances.

The calculation unit (Fig. 2) consists of two channels: one of the path intervals or time periods is measured in each channel. If the systems being realized are based on the measurement of paths covered by a body in given time intervals, then the signal from the photoelectronic multiplier is fed to input I, while the time marks are fed to input II. If the systems being realized are based on the measurement of time in which a body covers given path intervals, then the signal from the FEU [photoelectronic multiplier] is fed to input II, while the time marks - input I. The function of the automation unit is identical in both cases; therefore, subsequently, we will consider only the systems based on the measurement of paths.

Each channel contains a calculation decade unit, selector, automation unit, frequency divider unit and logical AND circuit. Frequency dividers together with logical AND circuit carry out the function of shaping the required time period - the gating pulse - during which the pulses coming from FEU are counted. The calculation decades determine the number of pulses received from FEU, as a result of which the path covered by a falling body is determined for the duration of the gating pulse.

The automation unit resets the calculation decades and frequency divider decades into the original position, generates the gating pulse which controls the selector and the pulse to terminate the calculation (start of the recording device RU).

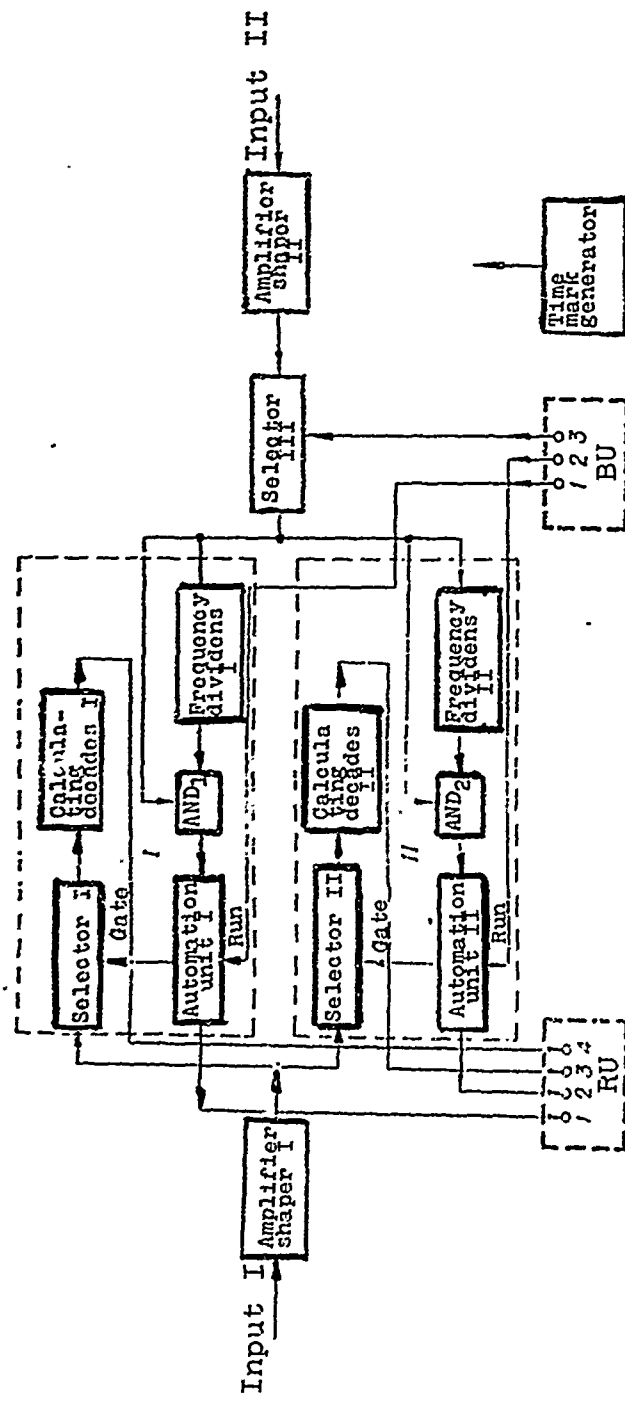


Fig. 2.

The operation of the calculation unit is somewhat different depending on whether or not the starting points of the measurement periods coincide. In the first case, to start the calculation the signal from the control unit BU opens selector III. The first time mark passes through the logical AND circuit to the automation units and actuates the time-calculation flip-flops. The time-calculation flip-flops operate and open the selectors. The next time mark will pass through any one of the AND circuits to the automation unit after the frequency divider controlling this AND circuit counts up a certain number of pulses, i.e., forms certain interval. This mark will act on the time-calculation flip-flop. The flip-flop will operate again after which the selector closes. The selector of the second channel will close when the frequency dividers of the second channel form a second given interval. After each measurement cycle the calculation decades and frequency divider decades are reset automatically into their original position.

In the second case, to start the calculation the pulse from the control unit is fed to automation unit I through contact I. This pulse prepares the system for measurements and resets the calculation and frequency divider decades. After this the first time mark passes through the logical AND circuit to the automation unit I and actuates the time-calculation flip-flop. Further, the same thing occurs as in the first case, i.e., channel I measures the first interval. The pulse to terminate the calculation, which is generated by the automation unit when the time-calculation flip-flop operates for the second time, is fed from automation unit I to automation unit II (from contact 1 of the RU to contact 2 of the BU) and it is the starting pulse for the automation unit II (pulse to start the calculation). Thus, the whole cycle is repeated for channel II where the second interval is measured.

The addition of a third channel to the calculation unit has resulted in the realization of the system without systematic errors (the so-called method of four stations).

Another modification of the calculation unit is based on the use of only one channel (Fig. 3). Such a calculation unit permits one to realize a measurement system based on the determination of paths covered by a body in given time intervals. In principle the operation of this unit is not different from that of the units described above. New units, delay multivibrator and a flip-flop, have been added so that the second run would be automatic. The multivibrator delays the second run for the time needed by the recording device for reading off the result obtained from the calculation decades. The introduction of a buffer memory between the calculation unit and the recording device permits one to reduce this delay to a minimum.

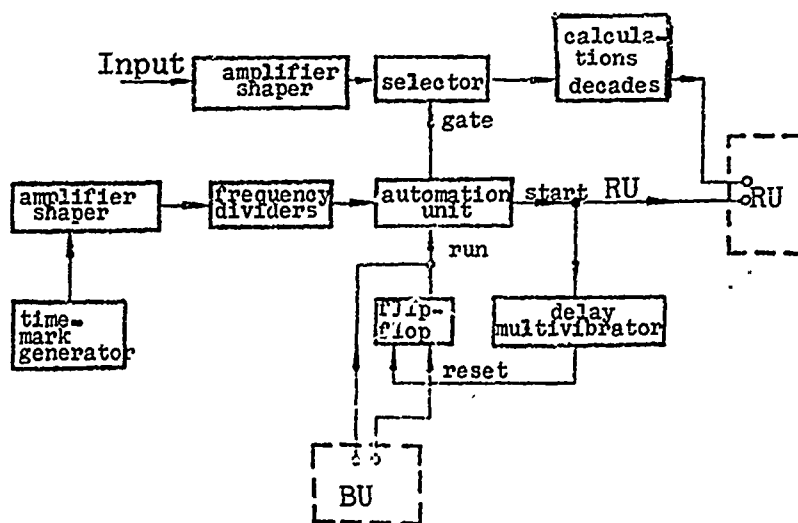


Fig. 3.

The recording device consists of a buffer memory, digital printer "Impremante-212," tape perforator PL-80 and a unit of decoders with indicating lights of type IN-4. The proper time sequence of operation of the instrument units is controlled by the control unit.

Let us look at the basic characteristics of the calculation unit. The high-speed operation of each channel exceeds 50 MHz. The durations of the leading and trailing edges of gating pulses controlling selectors do not exceed 2 ns. The durations of the shaping pulses at the 0.7 level comprise 5-7 ms. The time-mark generator

consists of a stable crystal oscillator with a signal frequency of 5 MHz, multiplier by 50 and divider by 5. The diurnal frequency instability comprises $\frac{\Delta f}{f} < 5 \cdot 10^{-9}$.

The mechanical and optical components of the gravimeter are mounted on a massive foundation. The microseismic vibrations of the foundation with acceleration \ddot{x} result in the fact that the interferometer, which is rigidly connected to it, measures the path of a test mass in a noninertial system of coordinates. Thus, with the use of, for example, a three-station method the measured paths will equal

$$S_1 = \frac{1}{2} g t_1^2 + V_0 t_1 - \int_0^{t_1} \left(\int_0^{t_1} \ddot{x} dt \right) dt,$$

$$S_2 = \frac{1}{2} g t_2^2 + V_0 t_2 - \int_0^{t_2} \left(\int_0^{t_2} \ddot{x} dt \right) dt$$

respectively. Solving the system of equations relative to g , we have:

$$g = \frac{2}{t_2 - t_1} \left(\frac{S_2}{t_2} - \frac{S_1}{t_1} \right) + \frac{2}{(t_2 - t_1) t_2} \int_0^{t_2} \left(\int_0^{t_2} \ddot{x} dt \right) dt + \\ + \frac{2}{t_1 (t_2 - t_1)} \int_0^{t_1} \left(\int_0^{t_1} \ddot{x} dt \right) dt.$$

The first term represents a true value of gravity acceleration g_0 , while the subsequent two - measurement error. If we take into account that the double integral due to the vibrational acceleration represents a vibrational displacement, then the last expression can be rewritten in the form

$$g = g_0 + \frac{2}{t_2 - t_1} \left(\frac{\bar{x}|_0^{t_2}}{t_2} - \frac{\bar{x}|_0^{t_1}}{t_1} \right) = g_0 + \frac{2}{t_2 - t_1} (\bar{x}_2 - \bar{x}_1).$$

In particular, if the main vibration spectrum lies at the low-frequency region $\omega_x < \frac{1}{t_2}$, then the change in \bar{x} during the measurement can be disregarded, which yields an obvious result:

$$g = g_0 + \ddot{\xi}_0.$$

Thus, the error due to the effect of "long-term" oscillations is equal to the acceleration of these oscillations.

The effect of the high frequency vibrations decreases due to the averaging. This is evident immediately when examining harmonic oscillations $\ddot{\xi}_0 \cos \omega_\xi t$. In this case

$$g = g_0 + \frac{2\ddot{\xi}_0}{t_2 - t_1} \left(\frac{1}{\omega_\xi^2 t_2} \cos \omega_\xi t \Big|_0^{t_2} + \frac{1}{\omega_\xi^2 t_1} \cos \omega_\xi t \Big|_0^{t_1} \right).$$

The term expressing the error achieves a maximum value when harmonic functions assume the value of a unit and minus unit, respectively.

Then

$$g = g_0 - \ddot{\xi}_0 - \frac{T_\xi^2}{2\pi^2 t_1 t_2}.$$

In other words the measurement error due to the "short-term" vibrations decreases proportionally to the square of the ratio of the period to the measurement interval.

The values of microseismic vibrations were measured in several laboratories (see, for example, [3]). Certain mean values can be characterized by the following numbers. In the frequency range 1-100 Hz the root-mean-square value of displacement has an order of 0.1-10 μm . At lower frequencies, beginning from 0.1-0.2 Hz, this value can increase by approximately one order. At frequencies below 1 Hz the accelerations become more significant in the gravimetry. Their magnitude seldom exceeds 1 mgal, generally remaining considerably smaller. However, we should mention that these numbers have a very approximate nature. Thus, the value of microseismic vibrations depends on the location where the measurements are made. In geological regions representing monolithic structures on a soft base, microseismic vibrations can be 1-2 orders less; in contrast, in the regions of increased seismicity they can be greater. Magnitude of microseismic vibrations depends on weather (especially in the region of low frequencies), increasing with strong winds, and on the time

of day. The measurements made by us showed that the means amplitude values of microseismic vibrations during the daytime have a value of approximately 0.7-1 μm , isolated bursts achieve a value of 1 μm . During the nighttime these amplitudes diminish by approximately 3-4 times.

Thus, if special measures are not taken, which would diminish the effect of vibrations of the foundation, then with each single measurement there is a random error of the order of 1 mgal. This error can be eliminated by three basic steps: 1) accumulation of measurement data and statistical processing; 2) taking measures to prevent vibrations and 3) introducing corrections into the measurement result.

When averaging the accumulated measurement results the random error decreases in proportion to the square root of the number of calculations. Since in our installation the measurement cycle comprises 12 s, on the order of 100 calculations (20 min of work) is required in order to decrease the error down to a level of 0.1 mgal. Accordingly, to reduce the error to the 0.02 mgal level, 2500 calculations are needed, which require approximately 10 h of work (taking into account the necessary pauses). When solving geophysical problems such as the determination of time variations of the gravitational and making the reference gravimetric grid more accurate, the fact that the installation has to operate for a long time, for example, 24 h, is not a drawback. Thus, for the present we chose to improve the accuracy by accumulating the results of single measurements. Evidently the same decision is applicable also in metrology.

The difficulties encountered in attempting to make this installation vibration-free are associated with the shortcomings of the low-frequency mechanical vibrational systems. Thus, for the usual system with a natural frequency of 1/20 s the deflection of springs under the weight of a mass comprises 100 μm . The compensation for this deflection, even to a value of 1 cm, requires the stability

of both the compensating force and the suspension itself with an error not worse than 10^{-4} .

The introduction of the automatic control systems has its own complications. The problem is somewhat simplified by the fact protection against vibration is needed only along one vertical axis. The problem concerning the vibration-free state of the platform is common to many problems in gravimetry and, due to its complexity, should be examined separately.

A third possible way is to introduce corrections. When a seismograph is used for introducing corrections an effective decrease in the effect of vibrations is possible in the frequency band in which the seismograph has a horizontal characteristic. This band begins with the natural frequency of the seismograph. With the introduction of the measures against vibration the effective action of the mechanical vibrational system begins only at frequencies which exceed the natural frequency of the mechanical vibrational system by several times, which in principle is not any different from that used in the seismograph. Therefore, the introduction of corrections is more effective under the effect of low-frequency vibrations.

We carried out experiments using low-frequency seismographs. Figure 4 shows a seismogram recording sample. The moment at which the measurement was terminated is clearly visible in terms of the impact created by a test mass at the moment of catching. The measurement time periods during which vibrational displacements of ξ_1 and ξ_2 are determined are reckoned from this moment. These values are then introduced into the calculation for determining the measured acceleration g . Since it is difficult to measure a displacement with an error less than 10-20%, this method permits one to reduce the value of a random error evoked by vibrations by not more than a value of $\beta = 5-10$. However, this permits one to sharply reduce (by β^2 times) the time necessary for the accumulation of the measurement results. Thus, this principle should be developed in the area where the speed of obtaining a final result is the deciding factor.

The complexity of protection against vibrations draws one's attention to the location where the gravimeter is situated. With regard to the latter it is natural to select areas with minimum seismicity, if, of course, at all possible.

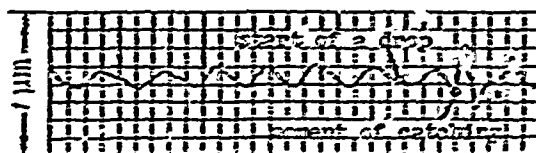


Fig. 4. Scanning speed, 50 mm/s.

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